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THE TOLERANCE OF GUINEA PIGS TO AIR BLAST WHEN MOUNTED IN SHALLOW, DEEP, AND DEEP-WITH-OFFSET CHAMBERS ON A SHOCK TUBE

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FOREWORD

This report, in the field of Blast and Shock Biology, is the second in a series describing experiments to determine the tolerance of animals to air blast in relation to their geometry of exposure. Guinea pigs were exposed to air blast while in shallow, deep, and deep-with-offset chambers on a shock tube, and the lethality was correlated with the pressure "dose" measured inside and outside the chambers.

The results apply only to the primary blast effect, to guinea pigs, and to conditions of these experiments, and might not apply to the full-scale situation.

This work is part of a broad research program aimed at a better understanding of human response to air blast and methods of protecting against it.

ABSTRACT

One hundred and eighteen guinea pigs were exposed to air blast in shallow, deep, and deep-with-offset chambers mounted on a shock tube. The LD_{50}-24 hours, in terms of the incident shock pressures measured adjacent to the chambers, was calculated by probit analysis to be 34.9 psi, 19.5 psi, and 26.8 psi for animals in the shallow, deep, and deep-with-offset chambers, respectively. According to the LD_{50} incident pressures, the shallow chambers offered the most protection against air blast; the deep chambers, the least.

Comparing the LD_{50}-pressure "dose" at the animals' location revealed little difference in their tolerance to overpressure, per se; i.e., LD_{50} reflected pressures measured by gauges within the deep and deep-with-offset chambers were 34.6 psi and 35.9 psi, respectively. The LD_{50} incident shock pressure of 34.9 psi in the shallow chambers was considered to be the "dose" at the animal's location in that instance.

The protection against blast provided by the three chambers and the response of animals to the particular pressure-time patterns encountered are discussed.

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This research was conducted according to the principles of Laboratory Animal Care as promulgated by the National Facility for Medical Research.

INTRODUCTION

Past studies indicate that biological response to air blast depends a great deal upon the shape of the pressure-time curve, or wave form.[1-7] For convenience and classification, wave forms may be termed "ideal" and "non-ideal" according to the nature of the initial portion of the pulse and the character of the pressure decay. Ideal wave forms are characterized by a near-instantaneous rise to maximal pressure followed by a decrease in pressure which falls exponentially with time. Non-ideal pressure pulses rise in a smooth manner, in steps, or in combinations of these; peak pressures do not occur at their leading edges and the character of the pressure fall may or may not be exponential with time.

Ideal blast waves are recorded in the open (free field) at appropriate ranges from high-explosive or nuclear detonations, and they can be produced in shock tubes.

In many instances, non-ideal wave forms arise as modifications of ideal blast waves when the latter enter structures or meet obstacles. Non-ideal wave forms also may occur from a nuclear detonation in the free field as a result of the interaction of a blast wave with a heat-absorbing surface.[8] They also can be generated in appropriately modified shock tubes.

Considerable information indicates that biological response to ideal blast waves depends upon the magnitude (peak) of the pressure and the duration of the positive pulse.[8-15] On the other hand, relatively few data exist relating biological tolerance to non-ideal blast waves.[1-7] All other factors being equal, animals apparently can tolerate higher pressures applied in a smooth manner or in two steps with a short time between the steps better than they can tolerate pressures applied in a single, near-instantaneous rise.

The form that the blast wave takes after entering a structure is related, among other things, to the volume of the structure, to the area and shape of the opening, and to the orientation of the entrance to the incident wave.[16] Thus, "geometric" scaling is needed to evaluate the pressure-time pattern characteristics of structures of a given geometry as a function of the incident shock wave in order that biological response may be related accurately to the proper variations in environmental pressure.

Preliminary experiments are reported here in which animals were exposed to air blast while in shallow, deep, and deep-with-offset chambers attached to the side wall of a shock tube. The biological response (death) is related to the incident shock pressures as well as to the pressure-time pulse recorded within the chambers.

METHODS

Shock Tube

An air-driven shock tube generated the air blast (Figure 1). The overall length of the tube was 76 ft 2 in., the diameter of its circular cross section was 23.5 in., and its walls were approximately 0.5-in. thick. A 5-ft section of the tube constituted the compression chamber (driver section) which was separated by Du Pont Mylar diaphragms from the 71-ft-2-in. expansion chamber (driven section). A 3-ft-6-in. test section was 47 ft 8 in. downstream from the diaphragm. There were 20 ft of tubing distal from the test section. In these experiments, the end of the expansion chamber was always open.

Test Section

The test section, with its four chamber-mounts, has been previously described.[5] In the current experiments, as noted in Figure 2, the chambers were arranged in three different geometries by using extensions and wooden blocks: (1) shallow chambers — 3 x 8 x 2.5 in. (approximately one animal-diameter deep); (2) deep chambers — 3 x 8 x 8 in. (approximately three animal-diameters deep); (3) deep chambers with offsets — 3 x 8 x 8 in. with a 3 x 8 x 2.5-in. "offset" oriented parallel to the long axis of the chamber. Each chamber was always placed end-on with respect to the incident shock front.

The shallow chambers were in positions "a" and "c"; the deep chambers in "a," "b," "c," or "d"; and the deep chambers with offsets in "b" and "d."

Animals

A total of 118 guinea pigs of both sexes (average body weight, 528 gm) were used in these experiments. Forty animals were exposed in the shallow chambers, 38 in the deep chambers, and 40 in the deep-with-offset chambers. Four animals, each in a single test chamber, were exposed tail-on to the incident shock during each test. Animals that survived were sacrificed with Nembutal and autopsied at 24 hours; therefore, the data reported herein represent 24-hour lethality.

Pressure Gauges

Piezo-electric gauges (Model S-2*) containing Lead Metaniobate sensing elements were used to measure pressure-time variation. The frequency response of the gauges was greater than 200 kcps. Signals from the gauges were fed through cathode followers* into Tektronix oscilloscopes (Model 535A) having Type L or Type 53/54C preamplifier plug-in units. Permanent pressure-time records were taken by photographing the sweep on the face of the cathode tube of the oscilloscope with a Polaroid Land camera. Gauges were calibrated with a piezo-electric gauge calibrator.[17]

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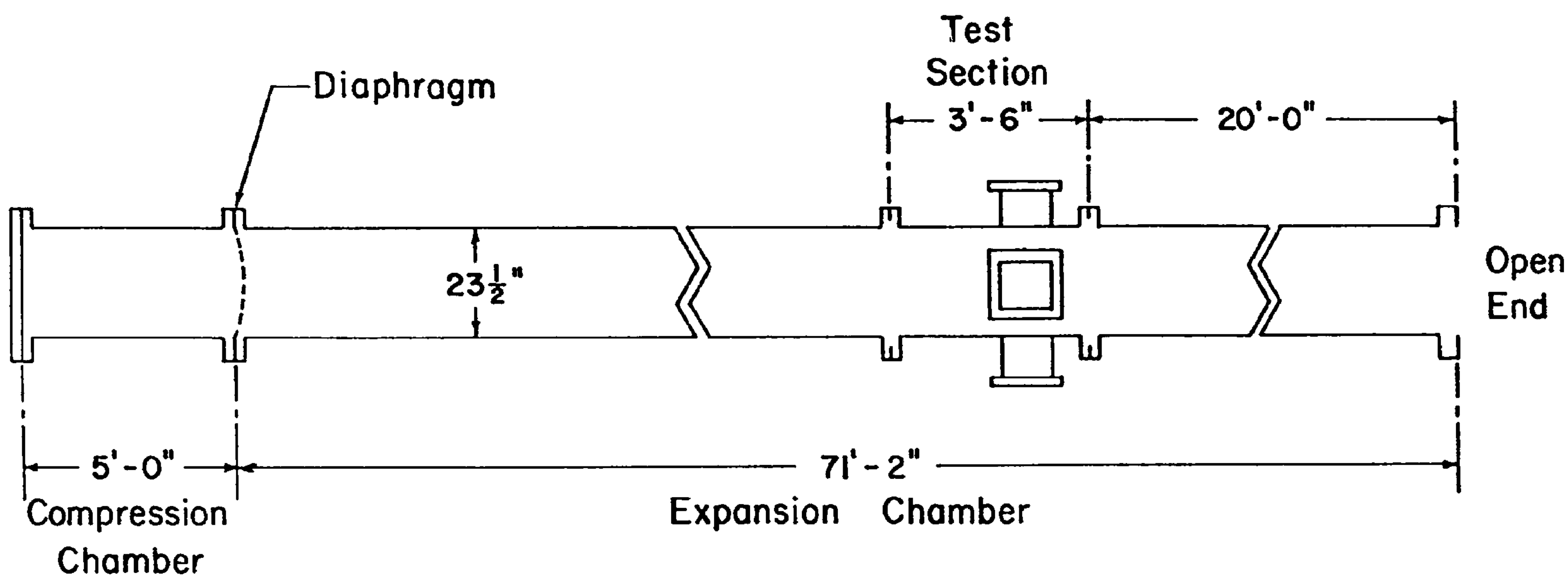
*Susquehanna Instruments, Bel Air, Md.



Shock Tube
Diagram

Figure 1

CROSS SECTION OF THE TEST SECTION
AT THE CHAMBERS

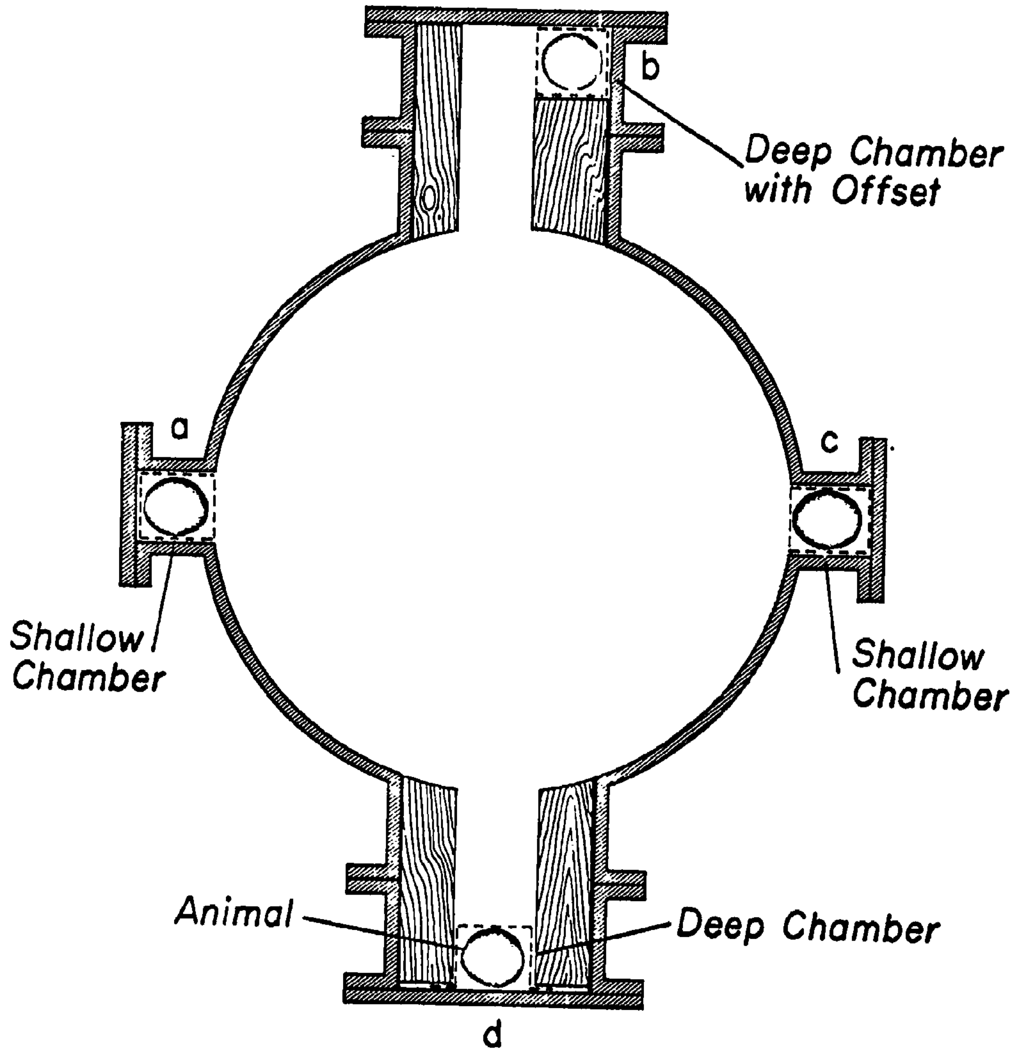


Figure 2

On every test, gauges were placed in the main body of the tube. Additional gauges were located in the lateral wall of the deep chamber and in the bottom of the deep-with-offset chamber when animals were exposed there. During many of the trials, gauges were also mounted at various points in the upstream and downstream walls of the chambers.

RESULTS

Pressure-Time Recordings

Figures 3, 4, and 5 contain pressure-time records associated with the shallow, deep, and deep-with-offset chambers. All illustrated records were taken with animals in the chambers and with driver pressures of 120 psi.

Figure 3 shows that the incident shock wave was "flat-topped" — typical of many waves produced in shock tubes. The duration of the "flat top" (the time the pressure remained near the incident shock level) was about 4 msec. The duration of the overpressure was about 40 - 42 msec (lower record, Figure 3). Throughout these experiments, the pressure durations ranged from approximately 40 msec to about 54 msec for low and high driver pressures, respectively.

As noted in Figures 4 and 5, the reflected pressures were higher in the deep and deep-with-offset chambers than in the incident shock wave. Moreover, the leading edge of the pressure curves in these chambers was altered from the single step associated with the incident wave. The pressure-wave forms varied at the downstream, lateral, and upstream walls of the same chambers, and the times to peak pressure were the longest at the upstream walls of the deep and deep-with-offset chambers.

Lethality Data

In Table 1, the 24-hour mortality is related to the incident shock pressures for each of the chambers and to the reflected pressures as measured within the deep and deep-with-offset chambers. Probit analysis was the method used to calculate the LD_{50}'s, regression line equations, and fiducial limits.[18] The incident shock pressures were first related to the percent mortality. The results of the probit analysis appearing in Figure 6 and Table 2 show that the LD_{50} incident shock pressures and 95-percent confidence limits computed for animals in shallow, deep, and deep-with-offset chambers were 34.9 psi (33.4 - 47.8 psi), 19.5 psi (17.4 - 21.0 psi), and 26.8 psi (24.2 - 29.6 psi), respectively. Each LD_{50} value was statistically different from the other two at the 95-percent confidence level.

The wide 95-percent confidence limit associated with the LD_{50} for animals in the shallow chambers was probably due to a number of factors. Three will be mentioned; namely, (1) the lack of data for the higher pressures, which in this present study, was because of the difficulty in generating pressures above 30 - 35 psi using an open, air-driven shock tube, (2) the small number of animals in each group, and (3) variability in the time of death which often encompasses a lethality time greater than 24 hours, particularly for exposures to the lower overpressures. Though these factors help explain why the data at hand "say" that the 95-percent confidence limits for the LD_{50} range from 33.4 to 47.8 psi, it needs to be pointed out that the figures represent an "artificial" situation. This is so because shock overpressures of between 45 and 50 psi will lethally injure 90 to 100 per cent of the guinea pigs with methodical regularity.

It has been pointed out previously that records from pressure gauges

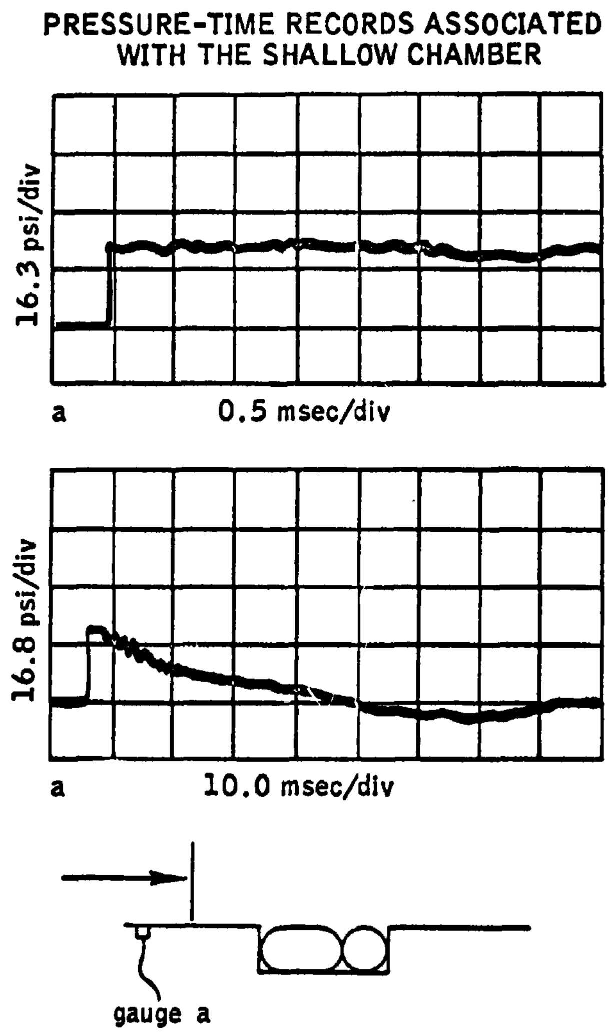

PRESSURE-TIME RECORDS ASSOCIATED WITH THE SHALLOW CHAMBER
16.3 psi/div
a
0.5 msec/div
16.8 psi/div
a
10.0 msec/div
gauge a

Figure 3

PRESSURE-TIME RECORDS ASSOCIATED
WITH THE DEEP CHAMBER

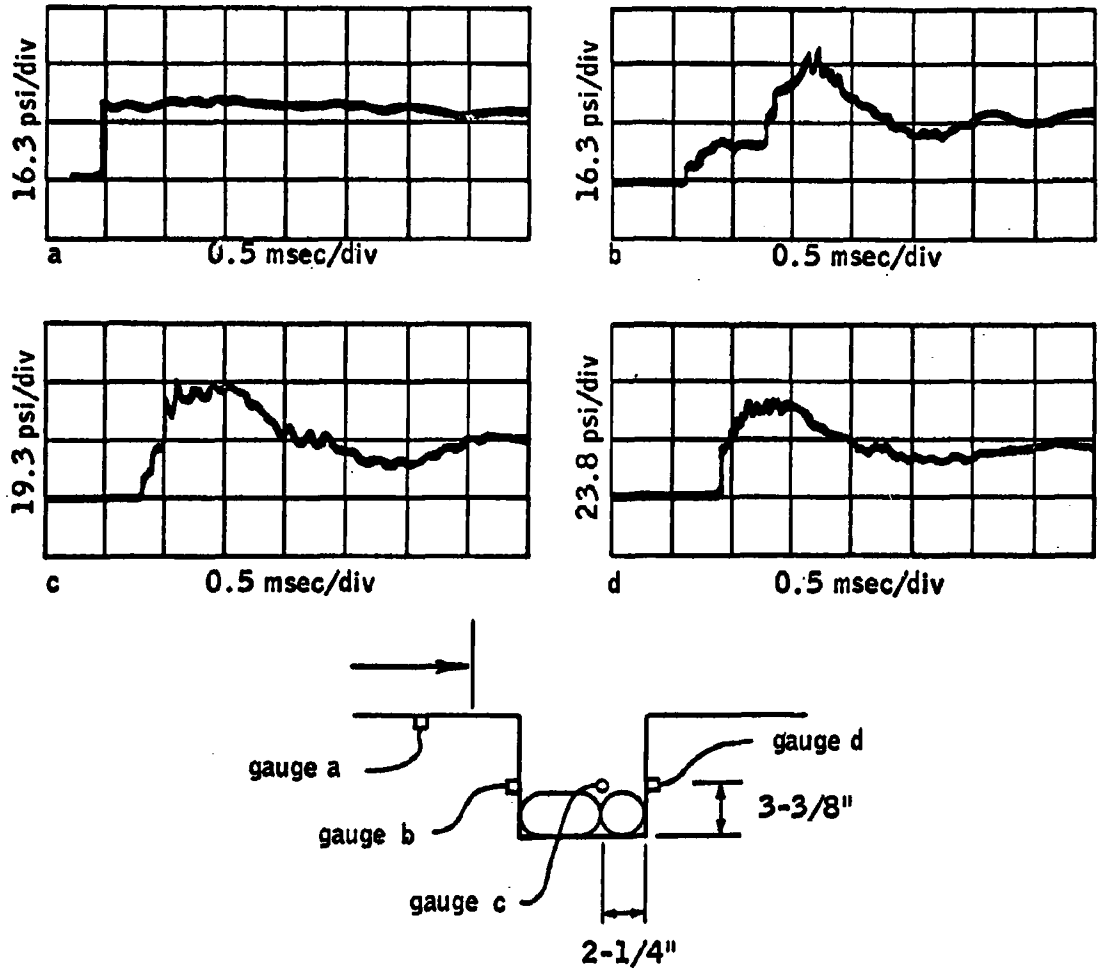


Figure 4

PRESSURE-TIME RECORDS ASSOCIATED WITH THE DEEP-WITH-OFFSET CHAMBER

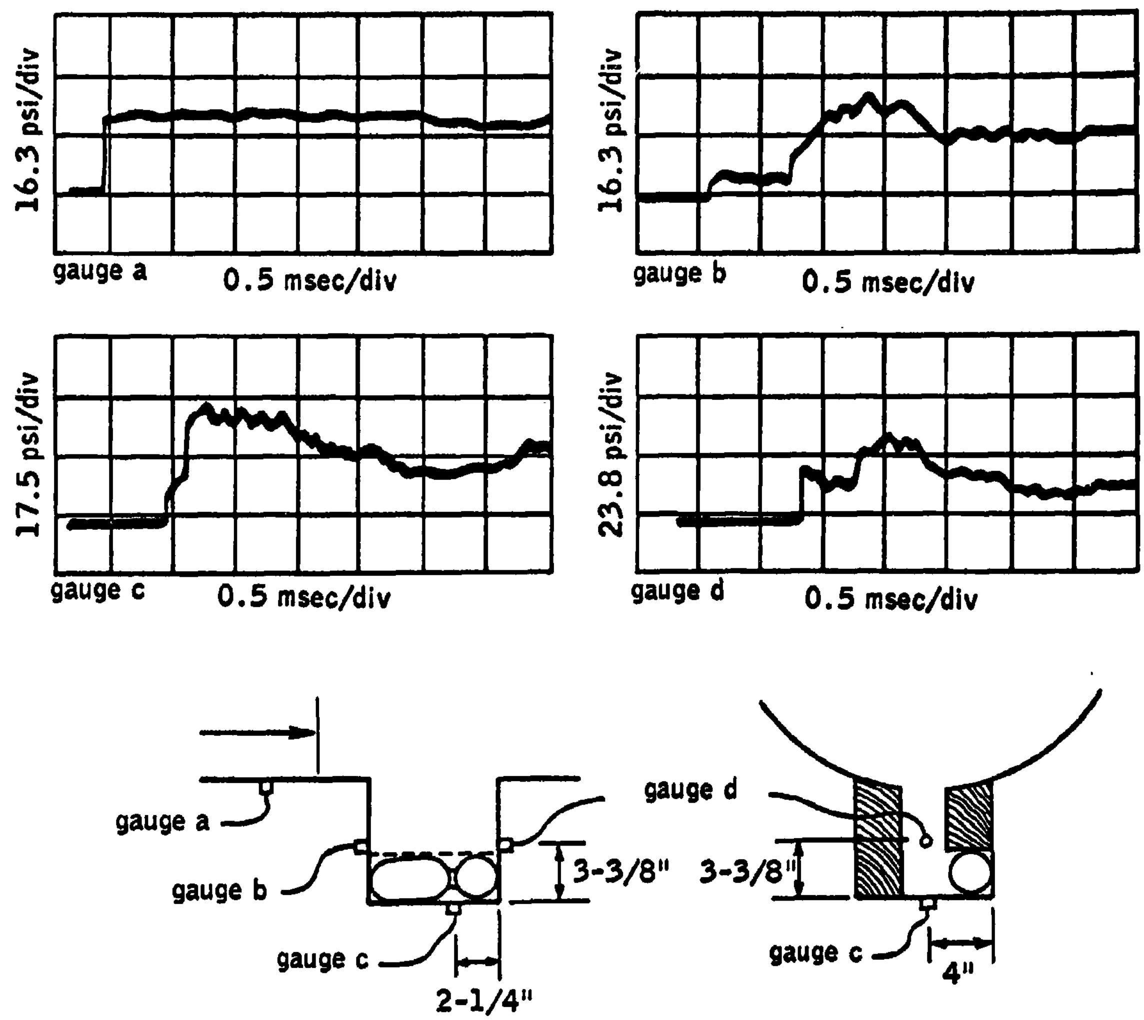


Figure 5

TABLE 1

THE RELATION BETWEEN MORTALITY AND OVERPRESSURE FOR GUINEA PIGS IN THE VARIOUS CHAMBERS

Group	Pressure, psi		Mortality	
	Incident Shock	Reflected Maximum	Number Dead / Total	Percent
Shallow Chamber:				
I	29.6[1]	-	1/10	10.0
II	32.2	-	1/10	10.0
III	33.4	-	3/10	30.0
IV	35.0	-	6/10	60.0
Deep Chamber:				
I	16.6[1]	30.2[2]	2/12	16.7
II	21.4	36.9	8/12	66.7
III	23.6	42.4	13/14	92.8
Deep Chamber with Offset:				
I	21.8[1]	29.8[3]	1/10	10.0
II	23.6	33.0	3/10	30.0
III	31.0	41.5	8/10	80.0
IV	35.0	42.8	9/10	90.0

[1] Measured in the wall of the tube adjacent to the chambers (Fig. 3).
[2] Measured in the side wall of the chamber (see Fig. 4, Record c).
[3] Measured in the floor of the chamber (see Fig. 5, Record c).

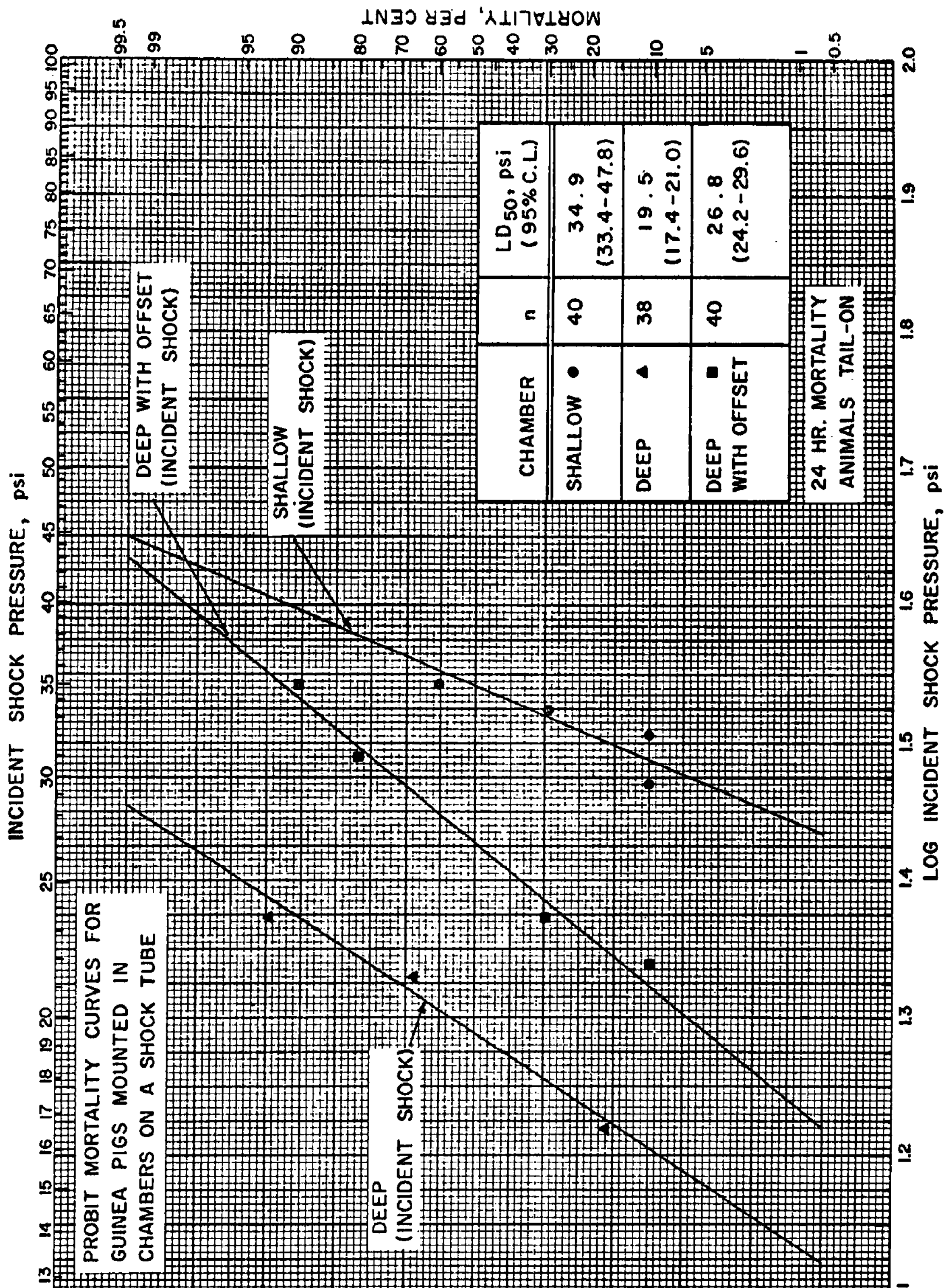

INCIDENT SHOCK PRESSURE, psi
MORTALITY, PER CENT
MORTALITY, PROBIT UNITS
LOG INCIDENT SHOCK PRESSURE, psi
PROBIT MORTALITY CURVES FOR GUINEA PIGS MOUNTED IN CHAMBERS ON A SHOCK TUBE
DEEP WITH OFFSET (INCIDENT SHOCK)
SHALLOW (INCIDENT SHOCK)
DEEP (INCIDENT SHOCK)
CHAMBER
n
LD50, psi (95% C.L.)
SHALLOW ● 40 34.9 (33.4-47.8)
DEEP ▲ 38 19.5 (17.4-21.0)
DEEP WITH OFFSET ■ 40 26.8 (24.2-29.6)
24 HR. MORTALITY
ANIMALS TAIL-ON

Figure 6

TABLE 2

RESULTS OF THE PROBIT ANALYSIS RELATING LETHALITY TO OVERPRESSURE

Chamber Geometry	Number of Animals	LD50, psi	Probit Equation Constants intercept, a	slope, b
Incident Shock:				
Shallow	40	34.9 (33.4 - 47.8)[1]	-30.856	23.247± 10.121[2]
Deep	38	19.5 (17.4 - 21.0)	-14.276	14.950± 3.961
Deep-with-Offset	40	26.8 (24.2 - 29.6)	-12.247	12.080± 3.008
Reflected Maximum:				
Deep	38	34.6 (31.5 - 37.2)	-20.303	16.435± 4.379
Deep-with-Offset	40	35.9 (33.0 - 38.8)	-18.799	15.299± 3.760

[1] 95-percent confidence limits.
[2] Standard error of the slope constant.

mounted as close to the animal's lung as possible best define the air-blast "dose" received.[3,5,6] In particular, for animals exposed in a geometry in which reflections occur, the gauge apparently should be at the downstream margin of the animal's lung.[3,5] Consequently, the probit analysis was applied to the mortality data in Table 1, and it related reflected shock pressure to lethality for animals in the deep and deep-with-offset chambers. Since the guinea pigs all but filled the shallow chambers, significant reflections did not occur; so the incident shock pressure was considered to be the "dose" at the animal's location.

Figure 7 compares the probit regression lines relating lethality to the maximal reflected pressures in the deep and deep-with-offset and to the maximal incident pressures at the shallow chambers. The LD_{50}'s, in terms of reflected pressure, were 34.6 psi (31.5 - 37.2 psi) and 35.9 psi (33.0 - 38.8 psi) for animals in the deep and deep-with-offset chambers, respectively. These LD_{50} values were not significantly different from each other nor were they different from the LD_{50} incident pressure of 34.9 psi (33.4 - 47.8 psi) calculated for animals in the shallow chambers (Figure 7, Table 2).

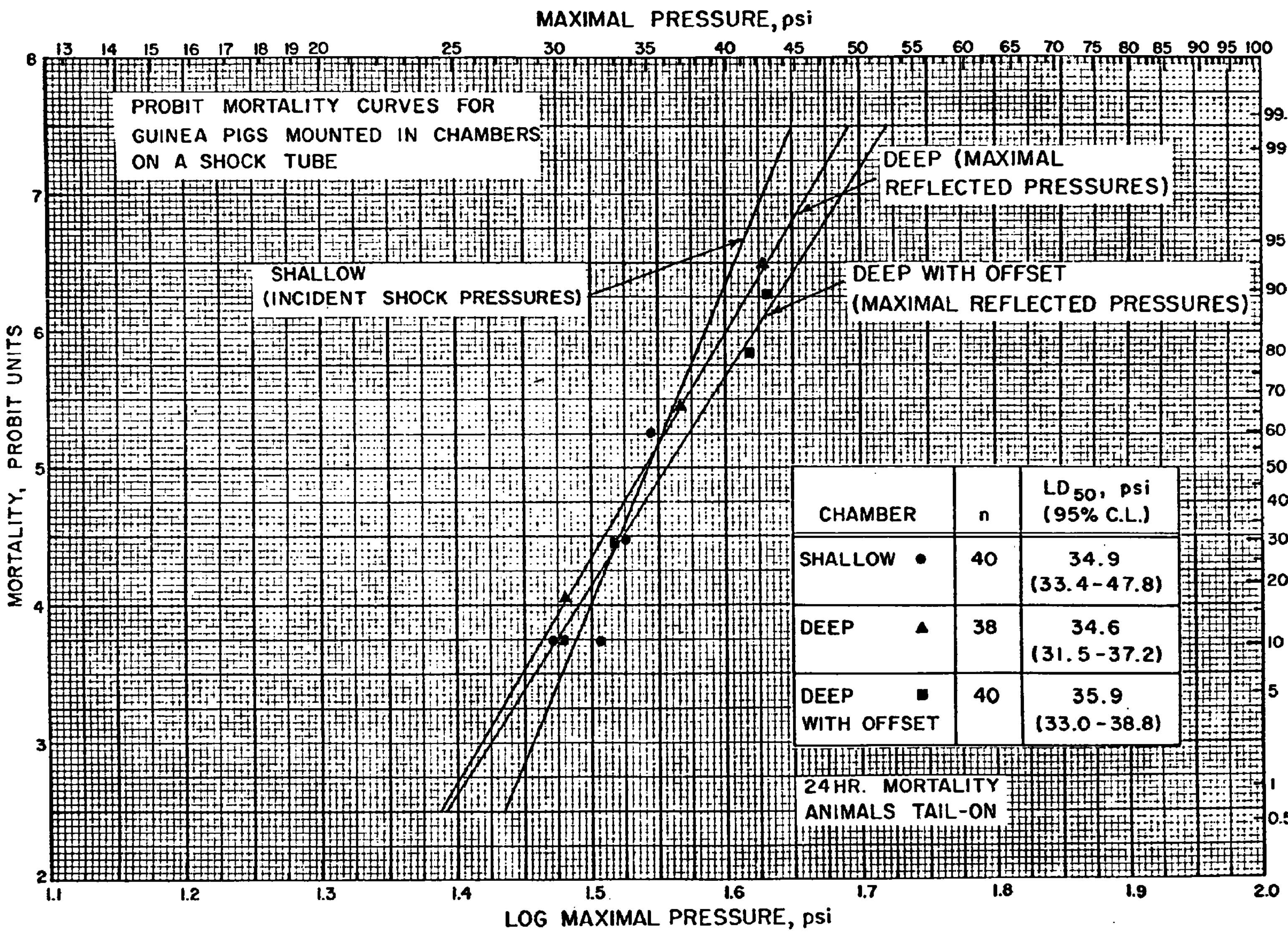

MAXIMAL PRESSURE, psi
13 14 15 16 17 18 19 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
PROBIT MORTALITY CURVES FOR
GUINEA PIGS MOUNTED IN CHAMBERS
ON A SHOCK TUBE
DEEP (MAXIMAL
REFLECTED PRESSURES)
SHALLOW
(INCIDENT SHOCK PRESSURES)
DEEP WITH OFFSET
(MAXIMAL REFLECTED PRESSURES)
CHAMBER
n
LD50, psi
(95% C.L.)
SHALLOW ● 40 34.9 (33.4-47.8)
DEEP ▲ 38 34.6 (31.5-37.2)
DEEP WITH OFFSET ■ 40 35.9 (33.0-38.8)
24 HR. MORTALITY
ANIMALS TAIL-ON
MORTALITY, PROBIT UNITS
8 7 6 5 4 3 2
MORTALITY, PER CENT
99.5 99 95 90 80 70 60 50 40 30 20 10 5 1 0.5
1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0
LOG MAXIMAL PRESSURE, psi

Figure 7

DISCUSSION

The results of this study can be discussed in relation to the protection against air blast provided by the three chambers and the response of animals to overpressure.

Protection Against Air Blast

The amount of protection against the shock wave afforded by the three types of chambers can be evaluated by comparing the incident shock pressures required to produce 50-percent lethality; by increasing order, they were 19.5 psi for the deep, 26.8 psi for the deep-with-offset, and 34.9 psi for the shallow chambers. The shallow chambers offered the most protection; the deep chambers, the least.

The protection gained by animals in the three structures may be illustrated in another way: According to the probit mortality curves in Figure 6, with an incident shock of 25 psi, one could expect less than 5-percent survival for animals in the deep chambers, about 65-percent survival in the deep chambers with an offset, and nearly 100-percent survival in the shallow chambers.

Analysis of the pressure-time recordings, as illustrated in Figures 4 and 5, revealed that the magnitude of the pressure in the incident shock nearly doubled after entering the deep chambers because of reflection from the downstream walls and the bottoms of those structures. Others have reported that reflected pressures of about twice the incident shock can occur in simple trenches.[19] The reader is referred to other studies for a more detailed account of air-blast filling of open structures and tunnels.[16, 19-23]

Tolerance to Overpressure

Comparing the LD50's, in terms of the pressure "dose" at the animals' lungs, revealed little difference in tolerance to overpressure, per se. The LD50 values were 34.6-psi reflected pressure, 34.9-psi incident pressure, and 35.9-psi reflected pressure for animals in the deep, shallow, and deep-with-offset chambers, respectively.

It should be emphasized here, however, that even though the pressure rose in a stepwise manner in the deep and deep-with-offset chambers, with respective times to maximal pressures of near 0.20 and 0.18 msec (Table 1), the LD50 values were not importantly different from those for guinea pigs exposed to a near-instantaneous-rising pressure pulse in the shallow chamber. The LD50's were also in agreement with those obtained for guinea pigs subjected to sharp-rising pressures of 6 to 8-sec duration (LD50, 36.6 psi)[4], 400-msec duration (LD50, 34.5 psi)[24], and 3 to 4-msec duration (LD50, 35.2 psi)[25] when the animals were exposed in cages mounted against the end-plates of shock tubes. Apparently, time intervals of 0.20 msec or less for the rise-times of the leading edges of the pressure pulses did not significantly alter the guinea pigs' tolerance to overpressure from what it would be for near-instantaneously rising pressures.

As mentioned earlier, a longer time to maximal pressure was recorded by gauges in the upstream wall than by those near the downstream wall of the deep chambers. It should follow then that if the animals were rotated from the tail-on to the head-on position (thereby subjecting their lungs to a slower-rising pressure pulse), there would be fewer deaths. Results from initial trials indicated that was indeed true. For instance, the LD_{50} reflected pressure for guinea pigs head-on in the deep chambers was calculated to be 47.4 psi compared with 34.6 psi for the animals oriented tail-on. The pressure "dose" was taken from recordings made by gauges located in the lateral wall about four inches from the downstream end of the chamber. The time to peak pressure at that point was near 0.40 msec. An incident shock of 25.5 psi was associated with the LD_{50} reflected pressure of 47.4 psi noted above.

These studies are being continued to determine the effect of varying chamber as well as animal orientation and to establish the protection provided by chambers of other designs.

The important question raised by this study was whether or not the results could be applied to large animals exposed to air blast in full-scale models of the chambers employed here. The question cannot be answered at the present time because of the uncertainties in predicting the magnitude of the pressures in the full-scale models as a function of the incident shock. And, more important, the tolerance of larger animals to overpressures that rise in a stepwise manner as a function of the time to maximal pressure is not known. Obviously, there is need for further laboratory work along with appropriate field tests.

SUMMARY

1. A total of 118 guinea pigs were exposed to air blast while mounted in chambers on a shock tube.

2. Three types of chambers were employed: shallow chambers that measured 3 x 8 x 2.5 in. — approximately one animal-diameter deep; deep chambers that were 3 x 8 x 8 in. — about three animal-diameters deep; and deep chambers with an offset that were similar to the "deep" except for a 3 x 8 x 2.5-in. "offset" parallel to the long axis of the chamber.

3. The chambers were always oriented end-on to the incident shock wave; the animals, tail-on.

4. Pressure-time measurements were taken with piezo-electric transducers mounted in the main body of the shock tube and in the walls and bottoms of the deep and deep-with-offset chambers.

5. The incident shock pressures required to produce 50-percent lethality in the three chambers were calculated by probit analysis. For animals in the chambers, the LD_{50}-24 hours and 95-percent confidence limits were as follows: shallow chambers, 34.9 psi (33.4 - 47.8 psi); deep chambers, 19.5 psi (17.4 - 21.0 psi); and deep-with-offset chambers, 26.8 psi (24.2 - 29.6 psi). Each LD_{50} value was statistically different from the other two at the 95-percent confidence level.

6. Judging from the LD_{50} incident shock pressures, the shallow chambers provided the most protection against air blast; the deep chambers, the least.

7. The reflected pressures measured on the lateral walls and bottoms of the deep and deep-with-offset chambers were about double the incident shock pressures.

8. The LD_{50} reflected pressures for animals in the deep and deep-with-offset chambers were calculated to be 34.6 psi (33.4 - 37.2 psi), and 35.9 psi (33.0 - 38.8 psi), respectively. These LD_{50} values were not significantly different from one another nor from the LD_{50} of 34.9-psi incident shock pressure considered to be the "dose" at the animal's location in the shallow chambers.

9. The protection provided against the air blast for animals in the different chambers was discussed along with the biological response in terms of the pressure-time pattern at the animal's location.

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